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A High-Power Continuous-Wave Mid-Infrared Optical Parametric Oscillator Module

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Abstract: We demonstrate here a compact optical parametric oscillator module for mid-infrared generation via nonlinear frequency conversion. This module weighs only 2.5 kg and fits within a small volume of 220 × 60 × 55 mm^3. The module can be easily aligned to various pump laser sources, and here we use a 50 W ytterbium (Yb)-doped fiber laser as an example. With a two-channel MgO-doped periodically poled lithium niobate crystal (MgO:PPLN), our module covers a tuning range of 2416.17–2932.25 nm and 3142.18–3452.15 nm. The highest output power exceeds 10.4 W at 2.7 µm, corresponding to a conversion efficiency of 24%. The measured power stability is 2.13% Root Meat Square (RMS) for a 10 h duration under outdoor conditions.

Keywords: mid-infrared laser; optical parametric oscillator; laser module

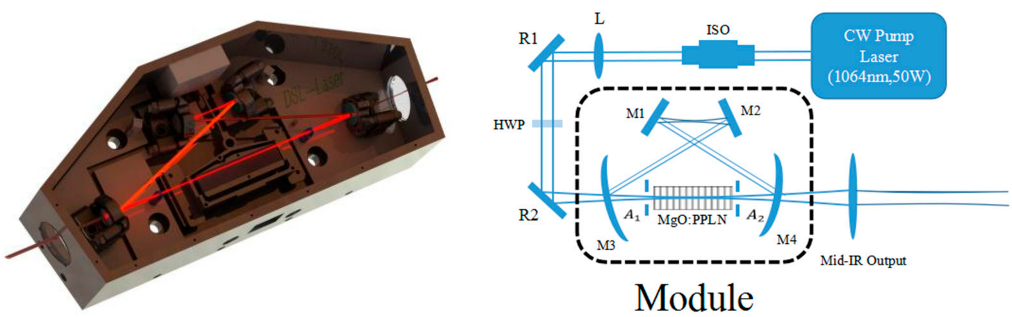
1. Introduction

Coherent mid-infrared (MIR) radiation is important for applications in many fields, such as gas sensing, ranging, spectroscopy, biochemistry, atmospheric science, and security [1–3]. Direct MIR generation can be achieved using quantum cascade lasers, but the output power, and thus the sensing and interaction distance, is limited [4,5]. On the other hand, high power MIR radiation can be generated from nonlinear optical frequency conversion in the form of optical parametric oscillators (OPOs) [6–9], and an output power up to 10 W has been reported [10]. However, most OPOs are built on optical tables with bulky optics and thus are not compatible for portable applications, such as moving vehicles based on the air, land or water [11–13].

In this article, we demonstrate an OPO module, which is embedded in a monolithic metal frame, with dimensions and a weight of 220 × 60 × 55 mm^3 and 2.5 kg, respectively. Such a module is compatible, and can be easily aligned, with any continuous-wave laser centered around 1064 nm for the MIR generation, and an ytterbium-doped fiber laser pump was used for our test. The MIR tuning ranges were 2416.17–2932.25 nm and 3142.18–3452.15 nm, using two channels of a periodically poled lithium niobate (PPLN) crystal with poling periods of 31.59 and 30.49 µm channels, respectively. At a maximum pump power of 50 W, the output power exceeded 10.4 and 9.1 W at 2.7 and 3.3 µm, respectively. The 10 h power stability was measured to be 2.13% root meat square (RMS) in a room without any special temperature stabilization.

2. Module Design

The frame of the MIR module was made from a single block of 7075 aluminum alloy for its high strength-to-weight ratio. As a result, we managed to construct the whole module with a weight of less than 2.5 kg. The configuration and schematic of our module is shown in Figure 1, and it was designed to be quickly aligned with any continuous-wave (CW) pump laser at around 1064 nm. The pump path into the OPO cavity was aligned to two irises in our module, and two high-reflection mirrors R1 and R2 can be used to steer the pump beam for the input alignment. Once the pump light matches with the irises, the module is ready for MIR generation. Inside the module is a symmetric ring OPO cavity. Cavity mirrors M1–M4 are all high-reflection-coated (R > 99.5%) at 1.35–2 µm (signal wavelength) and high-transmission-coated at 1064 nm (pump wavelength, T > 95%) and 2.3–5 µm (idler wavelength, T > 90%). M1 and M2 on both ends of the short arm are plane mirrors, while M3 and M4 on the long arm are concave mirrors with a curvature radius of 100 mm. The nonlinear medium is a periodically poled lithium niobate crystal (MgO:PPLN) doped with 5 mol % MgO with dimensions of 50 × 10 × 1 mm^3 and two channels with poling periods of 30.49 and 31.59 µm, for the dual band MIR generation around 2.7 and 3.3 µm, respectively. Both ends of the crystal are antireflection-coated at pump, signal, and idler wavelengths. The crystal temperature is controlled using a homemade oven, where the crystal mount is temperature-controlled with an accuracy of ±0.1 °C in a range between 20 and 170 °C. It is suspended from the oven enclosure by three ceramic tubes, which form a 2 mm air gap to reduce the thermal conductivity and further stabilize the temperature of MgO:PPLN. The surface of the crystal mount is finely ground for good thermal contact with the MgO:PPLN. A homemade miniaturized linear translation stage and electric actuator were built into the temperature-controlled oven for channel switching for the MgO:PPLN, and together they weigh only 10 g.



(**a**) (**b**)

Figure 1. The configuration of the module (**a**) and the optical schematic of the experiment (**b**). HWP: half wavelength plate; ISO: isolator; MgO:PPLN: MgO-doped periodically poled lithium niobate crystal; CW: continuous-wave.

3. Experiment and Results

In this experiment, we pumped our OPO module with a CW, linearly polarized, single-frequency Yb-doped fiber laser (IPG Photonics). The laser can deliver a maximum power of 50 W at 1064 nm with a beam diameter of 2 mm. Its spectral linewidth is only 70 kHz, which is one of the keys to achieving a narrowband MIR output. A free space optical isolator was used to protect the pump laser from unwanted back scattering, followed by a half-wave plate (HWP) to recover the polarization of 45° to a vertical polarization, and matched the Z-axis of the MgO:PPLN. A focal lens L with a focal length of 150 mm beam was used to focus the pump light to the center of the MgO:PPLN, with a beam waist radius of 58 µm. Considering the different diffraction properties at pump and signal wavelengths, we made the radius of signal light slightly larger than that of the pump light to optimize the overlap mode between them.

We measured the temperature tuning from the OPO module with both channels by varying the MgO:PPLN temperature from 20 to 170 °C. The MIR wavelength can be tuned from 2416.17 to 2932.25 nm or from 3142.18 to 3452.15 nm in 31.59-µm- and 30.49-µm-poled channels, as shown by the black and red curves in Figure 2, respectively.

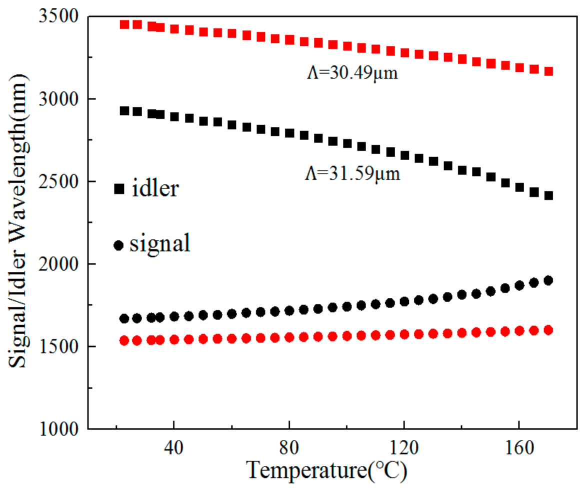


Figure 2. The output wavelength of the module as a function of the crystal temperature.

There are two wavelengths of special interest in the tuning range: 2.7 and 3.3 µm, which correspond to the absorption peaks of H–O and C–H bonds, respectively. The strong molecular rovibrational transitions that can be accessed with mid-IR laser sources allowed trace-gas sensing down to the parts-per-quadrillion level. We measured the output power from the MIR module at these two wavelengths. Figure 3 shows the output power as functions of the pump power when the MgO:PPLN temperature is set at 105.6 °C. The MIR wavelength was 2.7 µm for the 31.59-µm-poled channel, corresponding to a signal wavelength of 1.75 µm. For the 30.49 µm channel, the MIR and signal wavelength were 3.3 and 1.56 µm, respectively. The thresholds of the two above processes were 5.9 and 7.4 W, respectively. The output power for both wavelengths rose steadily as the pump power increased. The MIR output was limited by the maximum pump power of 50 W and exceeded 10.4 and 9.1 W at 2.7 and 3.3 µm, respectively. The maximum conversion efficiencies were 24% for 2.7 µm and 21% for 3.3 µm, respectively. The conversion efficiencies of the idler output were not linear because of the saturation of the pump depletion.

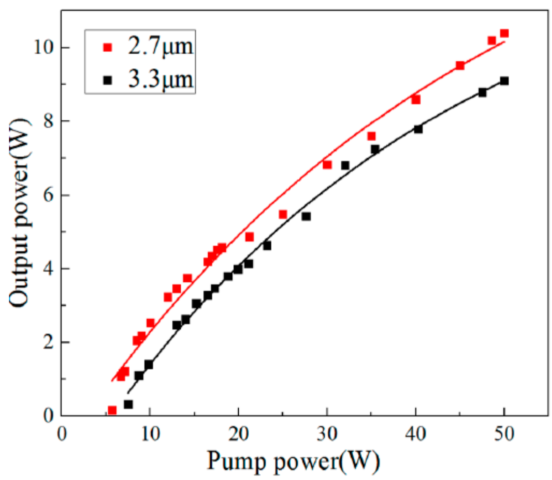


Figure 3. Output power of the module at 2.7 and 3.3 µm as a function of incident pump power.

The power stability of the OPO module was measured. The test lasted 10 h in a room without special temperature stabilization. The pump power was maintained at 35 W throughout the entire testing process. The MIR power was about 6.2 W at this pump power. As shown in Figure 4, the RMS of the MIR output power in 10 h was 2.13%. We measured the spectra characteristic using an optical spectra analyzer (YOKOGAWA AQ6375, YOKOGAWA, Tokyo, Japan), where the measured linewidth was limited by the instruction spectral resolution of 6 GHz. However, we could infer that our OPO was oscillating in a single longitudinal mode.

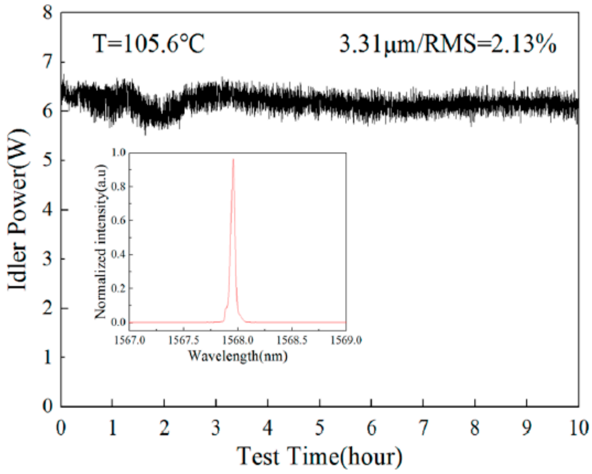


Figure 4. The long time power stability of 3.31 μm. Inset: the spectrum of the signal.

4. Conclusions

In summary, we have designed and fabricated an OPO module. The module is compact and confined, with dimensions and a weight of 220 × 60 × 55 mm^3 and 2.5 kg. The experiment results show that the module had a wide tuning range, a high power, and a stable output when a commercial Yb fiber laser was used as the pump laser. The MIR tuning ranges were 2416.17–2932.25 nm and 3142.18–3452.15 nm when two channels of a periodically poled lithium niobate (PPLN) crystal, with poling periods of 31.59 and 30.49 μm channels, respectively, were used. At the maximum pump power (50 W), the highest output power of the module exceeded 10.4 W at 2.7 μm and 9.1 W at 3.3 μm. To our knowledge, this is the best performing CW-OPO based on PPLN. The 10 h power stability at 3.31 μm was measured to be 2.13% RMS under outdoor environment. We believe that such a compact, tunable, stable, and high-power OPO module can be used as the core part of a number of mid-infrared laser sources. Its promoting effect in the relevant industries is foreseeable.

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Author Contributions: Zhenda Xie and Xinjie Lv conceived and designed the experiments. Yichen Liu, Jian Ning, Gang Zhao and Xukai Xie performed the experiments. Yichen Liu and Zhenda Xie wrote the paper, and Shining Zhu supervise the whole work.

Conflicts of Interest: The authors declare no conflict of interest.

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